

RL-TR-95-150
Final Technical Report
August 1995



PHYSICALLY ADAPTIVE ANTENNAS

University of Maryland

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ARPA Order No. A150



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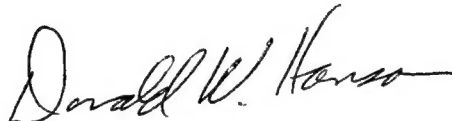
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PHYSICALLY ADAPTIVE ANTENNAS

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Contractor: University of Maryland
Contract Number: F30602-93-C-0184
Effective Date of Contract: 29 Jun 93
Contract Expiration Date: 29 Dec 93
Short Title of Work: Physically Adaptive Antennas
Period of Work Covered: Jun 93 - Oct 93

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This research was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by Richard Fedors, RL (OCPC), 25 Electronic Pky, Griffiss AFB NY 13441-4515.

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REPORT DOCUMENTATION PAGE

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Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE August 1995		3. REPORT TYPE AND DATES COVERED Final Jun 93 - Oct 93	
4. TITLE AND SUBTITLE PHYSICALLY ADAPTIVE ANTENNAS				5. FUNDING NUMBERS C - F30602-93-C-0184 PE - 62702F PR - A150 TA - 00 WU - 01	
6. AUTHOR(S) Dr. Ping-Tong Ho					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Maryland Department of Electrical Engineering College Park MD 20742				8. PERFORMING ORGANIZATION REPORT NUMBER N/A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Advanced Research Projects Agency 3701 North Fairfax Drive Arlington VA 22203-1714 Rome Laboratory (OCPC) 25 Electronic Pky Griffiss AFB NY 13441-4515				10. SPONSORING/MONITORING AGENCY REPORT NUMBER RL-TR-95-150	
11. SUPPLEMENTARY NOTES Rome Laboratory Project Engineer: Richard Fedors/OCPC/(315) 330-3144					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A reconfigurable antenna concept, consisting of a semiconductor illuminated by an optical or electron source, was studied. With appropriate illumination, mobile charge carriers excited from the valence band to the conduction band can form a conducting antenna pattern in the semiconductor material. Calculations of gain and radiation resistance for linear dipole and "bow-tie" layouts were completed to estimate source power requirements and practical wavelength limits for such an antenna. Significant findings were that source power for writing a reconfigurable antenna increases as the square of the radiation wavelength; and that semiconductor material permittivity limits antenna efficiency to about one-tenth that of a comparable free-standing antenna. Frequency agility in the antenna may be possible using an electronically controllable liquid crystal display, semiconductor laser array, or electron emitter tips.					
14. SUBJECT TERMS Antennas, Reconfigurable, Semiconductor, Linear dipole, Bow-tie, Radio frequency				15. NUMBER OF PAGES 60	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		

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The Reconfigurable Antenna and Objective of Study

The reconfigurable antenna under study consists of a semiconductor illuminated by an optical or electron source. The illumination is non-uniform over the semiconductor. The illuminated part becomes conducting and forms the antenna. The conducting pattern can be controlled electronically, making the system agile. With light, the pattern can be illuminated with semiconductor laser arrays whose driving currents are controlled electronically, or with an incoherent source through a liquid crystal display matrix whose transmission is controlled by a computer. With electrons, emitter tips can be controlled with electrical signals. In both cases, mobile charge carriers are created in the semiconductor by exciting electrons from the valence band to the conduction band. The excitation energy needed per electron is the bandgap energy. The key question is whether usable antennas can be written with practical source (optical or electron) powers, and over what frequency range. This study endeavors to answer this question. A summary of the findings of this study follows immediately.

Summary of Findings of this Study

The study finds that:

(1) The source (optical or electron) power needed to write a reconfigurable antenna on a semiconductor *increases with the square of the radiation wavelength*, thus exacting a heavy price on low-frequency operations. For silicon, the optical power needed to write an antenna one wavelength long at 1 GHz is about 300 watts, and electron excitation requires about 1 kW for the same antenna;

(2) Because the permittivities of semiconductors are usually 10 times that of vacuum, an antenna on semiconductors, reconfigurable or metallic, is about 10 times less efficient as a free-standing antenna of the same electrical structure;

(3) Because of current decays in the necessarily resistive reconfigurable antennas, a single antenna of dimensions larger than a wavelength is hard to realize. For high gains, an array of smaller antennas has to be used;

(4) Wire-type antennas are suitable for directional excitation sources like lasers and micro-tip emitters; large aperture antennas, for flood sources like the flash lamp.

(5) For reasons stated above, practical reconfigurable antennas are limited to elementary structures for applications above a GHz or so, if the antenna systems are to be inexpensive and simple.

Establishing Criterion

The conductivity of patterns written on a semiconductor by light or electrons is proportional to the light or electron power incident on the semiconductor, and in practice cannot be made as high as that of metal. It means then that the reconfigurable antenna cannot be as effective as the metallic one, but can only approach the metallic in the limit of infinite source power. A criterion must be established to determine the feasibility of reconfiguration. There are two obvious parameters to determine the performance of an antenna: the gain and the radiation efficiency. Two antennas of very different efficiency can have the same gain, for example, the very inefficient short Hertzian dipole has almost the same gain at all directions as the much more efficient half-wave dipole. Therefore for this study, we will use efficiency as measured by the radiation resistance, and take the required source power as the power needed to induce sufficient conductivity so that the reconfigurable antenna radiates half as effectively as a metallic antenna of the same structure. By reciprocity, the same antenna used for reception will be half as effective as the metallic reference. Beyond this point of -3 dB efficiency, calculations reported below indicate that the radiation effectiveness increases much more slowly as source power increases.

Estimate of Required Source Power and Scaling

An order-of-magnitude estimate of the minimum required optical or electron power for writing a reconfigurable antenna can be made as follows. Most radiating systems have characteristic impedance of 50Ω to 100Ω . For microwave structures on dense dielectrics, characteristic impedances are reduced by the refractive index, typically 3 to 4 in semiconductors, therefore the resistance of the antenna pattern cannot be much higher than about 20Ω , or mismatch alone will render the antenna ineffective. The minimum source power can be estimated to be the power needed to reduce the resistance of the antenna pattern on semiconductor to 20Ω . Consider electrons or light of power P penetrate to depth d in the semiconductor to create an antenna strip of width w and length L , current flowing along L (Fig. 1). If a is the fraction of P absorbed by the semiconductor for exciting electrons from the valence to the conduction band across the bandgap E_g , and τ is the electron lifetime, then the electron density n can be calculated by balancing power to be:

$$n = aP\tau / (E_g Ldw) , \quad (1)$$

whence the resistance R along L is:

$$R = L^2 E_g / (e\mu a P \tau) \quad (2)$$

where μ is the electron mobility and e the electron charge. Any antenna of sufficient gain and directivity, which roughly scale as $(\text{size}/\lambda)^2$, must have a size of at least one wavelength λ . Equating L with λ in Eq. (2) yields the minimum source power required:

$$P = \lambda^2 E_g / (e\mu a \tau) \quad (3)$$

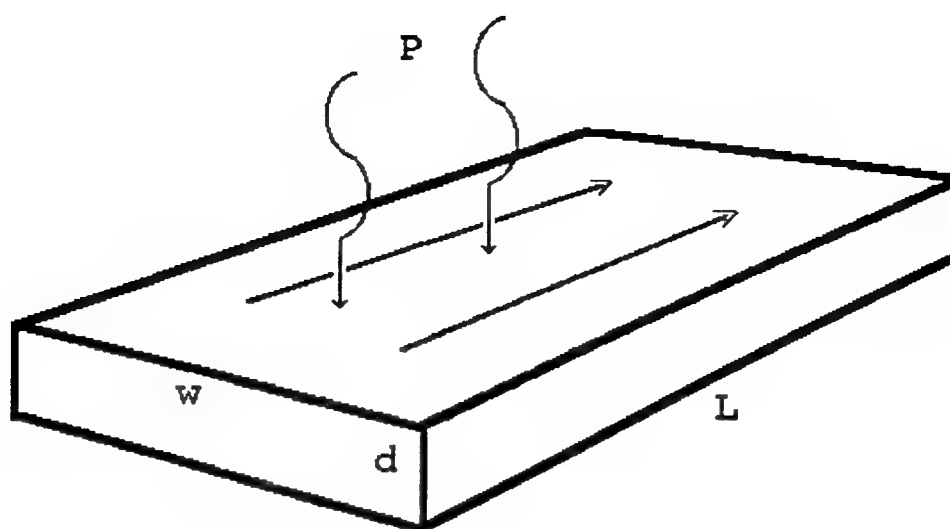


Figure 1 Geometry of Semiconductor
under Excitation

The significance of this equation is that the **required power increases with the square of the wavelength**. The wavelength λ is the wavelength in semiconductor, typically about 0.3 of that in vacuum.

For light sources in the visible and near infrared, the photon energy is close the bandgap energy E_g , so $a \sim 1$ except for narrow bandgap materials like germanium. For low-energy (< few keV) electrons, typically $3E_g$ [1] is needed to excite one electron to the conduction band, and $a \sim 0.3$. Using established material parameters, the minimum required powers are listed in Table 1 for silicon and germanium. (The carrier lifetime of silicon depends on many factors - impurities, defects, processing steps, and can vary from under 1 μ s to 1 ms. The more typical value of 20 μ s is used in Table 1. Also, because of the dielectric mismatch between vacuum and semiconductors, about 30% of incident light is reflected.)

Table 1
Minimum Source Power for Reconfigurable Antennas

	Silicon	Germanium
Optical Source (watts)	$3\lambda^2$	$0.04\lambda^2$
Electron Source (watts)	$10\lambda^2$	$0.06\lambda^2$
	Wavelength λ in cm	

For example, for 1 GHz in silicon, $\lambda \sim 10$ cm, the minimum required optical power is 300 Watts, which we consider practical.

The estimates given here are validated by more accurate calculations shown below for several cases.

Calculations on Resistive Antennas

(i) General Discussions

For more accurate estimates of the required source power, calculations have been performed on two representative antenna structures with finite electrical resistivity. The antennas are: (1) linear dipole; and (2) "bow-tie." The linear dipole is the simplest useful antenna, out of which other more complicated antennas of higher directionality and gain can be constructed. Directional sources like lasers and electron beams can selectively write linear dipoles efficiently. The bow-tie is a large-aperture, broad-band antenna suitable for flood sources like the flash lamp. Since the cross-sectional area of the conducting path of the bow-tie increases as the distance from the terminal increases, the resistance decreases as the current flows towards the end of the antenna, which to some degree counter-balances the effectively reduced antenna length due to current decay, which is accomplished without non-uniform illumination.

Throughout the calculations, we have followed the standard simplification of ignoring the reaction of the radiation field on the current distribution [2]. We assume an excitation current of given amplitude and frequency feeding the antenna, the current propagates along the resistive antenna and radiates. The total radiated power divided by the current squared yields the radiation resistance, the measure of radiation efficiency. By reciprocity, the radiation resistance also measures the reception efficiency of the antenna. The radiation impedance of the resistive antenna is different from that of the conventional antenna. We have ignored the additional problem of impedance matching, since it is only incidental to the basic question of power source requirement. In any case, the difference is about a factor of 2 in the final radiation efficiency.

In general, the more exact calculations shown below confirmed the 1st order estimate presented in the last section.

A resistive line is modeled by a distributed series resistance per unit length $R'[2]$, in addition to the standard series inductance/length L' and shunt capacitance/length C' (Fig. 2). All time-dependence is expressed by $e^{j\omega t}$, where ω is the angular frequency of the radiation. The propagation constant γ along the resistive line is complex:

$$\begin{aligned}\gamma &= (j\omega C'R' - \omega^2 L'C')^{1/2} \\ &= jk(1 + x_1)^{1/2} \exp(-0.5j \tan^{-1} x_1)\end{aligned}\quad (4)$$

where $k = \omega(L'C')^{1/2}$ is the propagation constant when the line is lossless, and

$$x_1 = R'/(kZ_0) \quad (5)$$

is the normalized resistance/length, with $Z_0 = (L'/C')^{1/2}$ the characteristic impedance of the lossless line. The real part of γ is the attenuation constant; the imaginary part, the propagation constant. Since the propagation constant depends on R' , finite resistance causes both attenuation of the voltage and current waves as well as phase shifts.

The relationship between resistance/length R' and the incident source power/length $P'=P/L$ is readily obtained from Eqn (2) (Fig. 1):

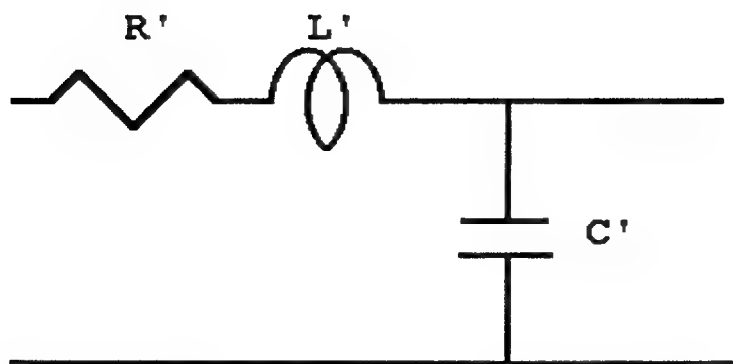


Figure 2 Model of an Infintessimal
Section of a Resistive Line

$$R' = E_g / (P' e \mu a t)$$

(6)

This relationship will be used in all subsequent calculations.

In addition to the obvious effect of reduced radiation efficiency, finite resistivity in a long antenna changes the radiation pattern. First, if the resistivity is constant along the antenna line, the current decays from the terminal towards the ends, effectively shortening the length of the antenna and increasing the angular distribution of radiation. Secondly, the additional phase shift caused by the resistive loss changes the phase relationship between the radiation fields generated by the different segments of the antenna, and the radiation pattern changes as a consequence of the changed interference pattern.

Other antennas can be modeled as a multiple of line antennas, so the comments on resistive line antennas above also apply. In particular, the sheet current in the bow tie antenna studied in this work is modeled by several line loops.

Boundary conditions used are zero current at open ends of a line, and zero voltage at shorted ends [2].

Finally, there is one incidental but important difference between a free-standing metallic antenna and an antenna on a semiconductor wafer. Semiconductors usually have very high dielectric permittivities, typically 10 times that of vacuum. Thus the wavelength in semiconductors are roughly 3 to 4 times shorter than in vacuum, i.e., the physical dimensions of an antenna on a semiconductor are shorter than those of a free-standing antenna of the same electrical dimensions by a factor of 3 or 4. But the radiation is into

the vacuum, so the antenna on a semiconductor has an effectively reduced size, leading to lower efficiency. By dimensional analysis, it can be shown that the efficiency is reduced by about the ratio of permittivities, i.e., about a factor of 10, which is borne out by numerical calculations. The wave vector and wavelength in semiconductor (vacuum) will be denoted as k (k_0) and λ (λ_0). The relationships between these quantities are: $k = nk_0$, $\lambda = \lambda_0/n$ where n is the refractive index of the semiconductor. For all the calculations below for silicon, $n=3.45$.

The general discussions above are in terms of radiating antennas. By reciprocity, the same apply to receiving antennas.

Formulas used in the following calculations are collected in Appendix I. Calculations were carried out on a personal computer with the software *Mathcad* for the linear antenna, and on a Sun workstation with codes written in C for the longer procedures for the bow tie; C programs written for this contract are listed in Appendix II.

Calculations are performed for optical illumination of silicon. *Source power for optical illumination of germanium, and electron excitation of silicon and germanium, can be found by scaling using the values in Table 1.*

(ii) The Linear Dipole

The symmetric linear dipole antenna, illustrated in Fig. 3, has been studied with respect to its radiation pattern, resistivity/length, and radiation resistance. Because of azimuthal symmetry, radiation only varies with θ . Comparisons have been made between a free-standing metallic antenna and one on a semiconductor wafer.

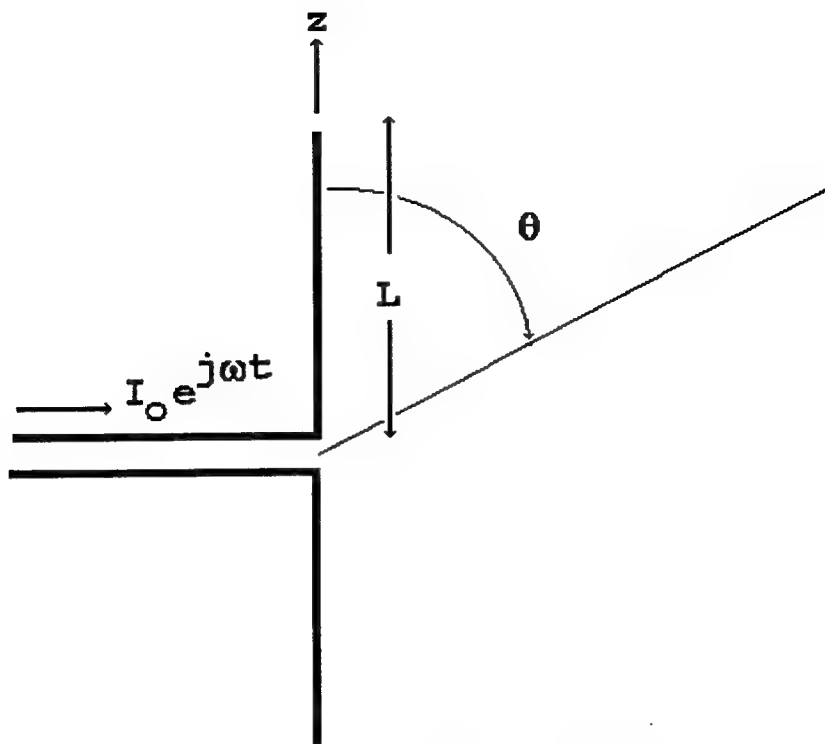


Figure 3 Linear Dipole Antenna

(a) Lossless Antennas For a lossless antenna, free-standing or on semiconductor, the radiation pattern, and therefore directional gain, does not change significantly for $2L$ up to one wavelength ($kL=k_0L=\pi$) (Fig. 4(a) and 4(b)). The radiation resistance, however, peaks at one wavelength (Fig. 5(a) and Fig. 5(b)). Fig 5 shows that the radiation resistance is about 10 times lower for the antenna on silicon than free-standing. For optimal performance, the antenna on silicon should be made one wavelength long ($1-\lambda$), which is the simplest useful antenna. Again, the wavelength is for silicon, therefore the *physical* length of the $1-\lambda$ antenna is n or 3.45 shorter than the wavelength in vacuum, which is still shorter than a free-standing, $1/2-\lambda$ antenna. The following calculations will therefore be on the $1-\lambda$ antenna on silicon.

(b) Resistive $1-\lambda$ Antenna on Silicon, Uniform Illumination

Resistive loss is introduced in the antenna line by Eqn. (4) via the dimensionless parameter x_1 which is related to the resistance/length and the incident power/length by Eqns. (5) and (6). It is assumed that the illumination on silicon is uniform, so that the resistance is constant along the antenna line. Fig. 6 shows the radiation resistance R_{rad} of the $1-\lambda$ antenna vs x_1 . At $x_1=0.22$, the R_{rad} has decreased by a factor of 2 from the perfectly conducting case ($x_1=0$), i.e., the efficiency of the antenna has dropped by 3 dB. At this point, the total source power needed to create the antenna can be found from Eqns (5) and (6) to be $\sim 2\lambda^2$ Watts for optical illumination with λ in cm. This power level agrees well with the estimate presented earlier.

(c) Resistive $1-\lambda$ Antenna on Silicon, Non-uniform Illumination The current in the uniformly illuminated antenna above decays by $1/e$ in a distance of about 1.4λ for $x_1=0.22$, when R_{rad} drops by 3 dB, thus effectively

Figure 4 a Directional Gain for Different Antenna Lengths $k_0 L$
Free-standing Antenna

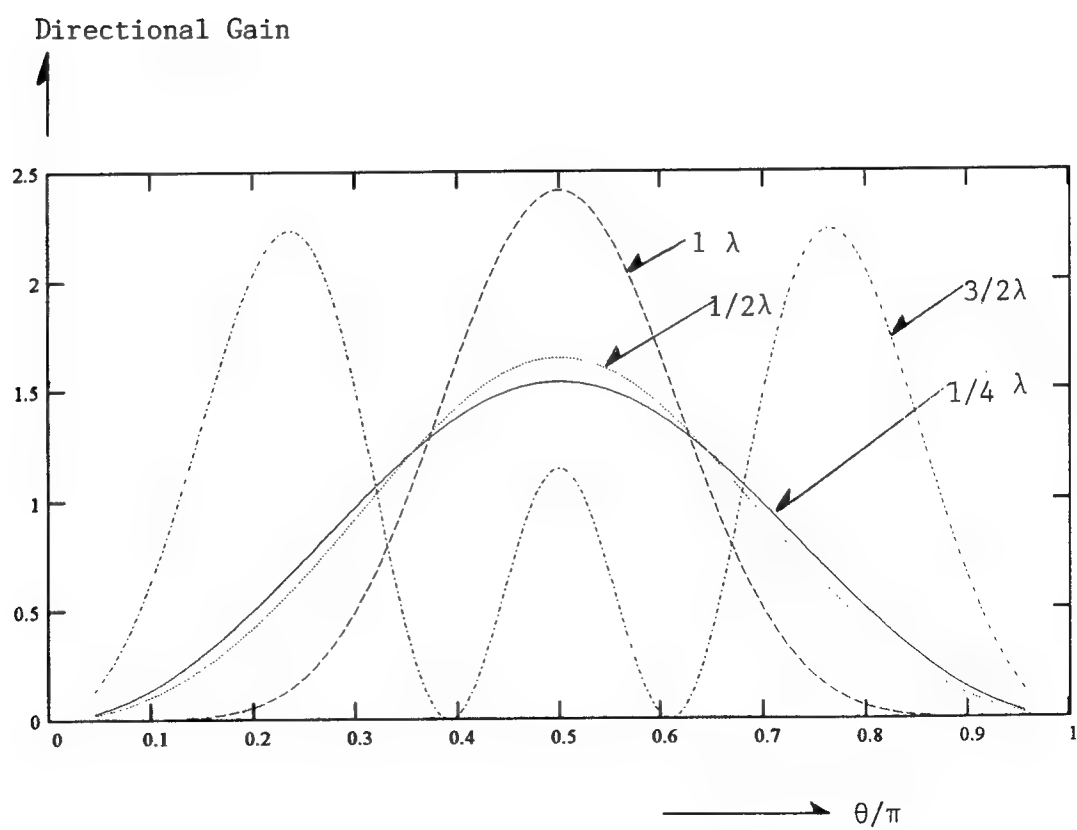
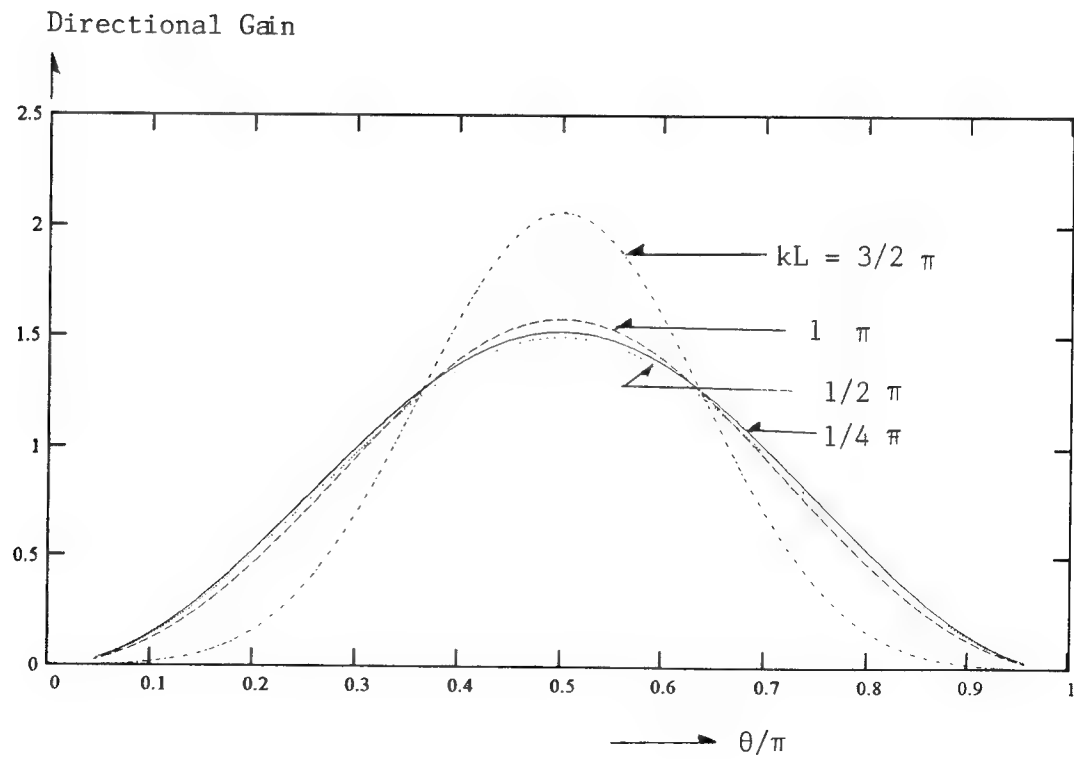


Figure 4b Directional Gain for Different Antenna Lengths kL
Antenna on Silicon



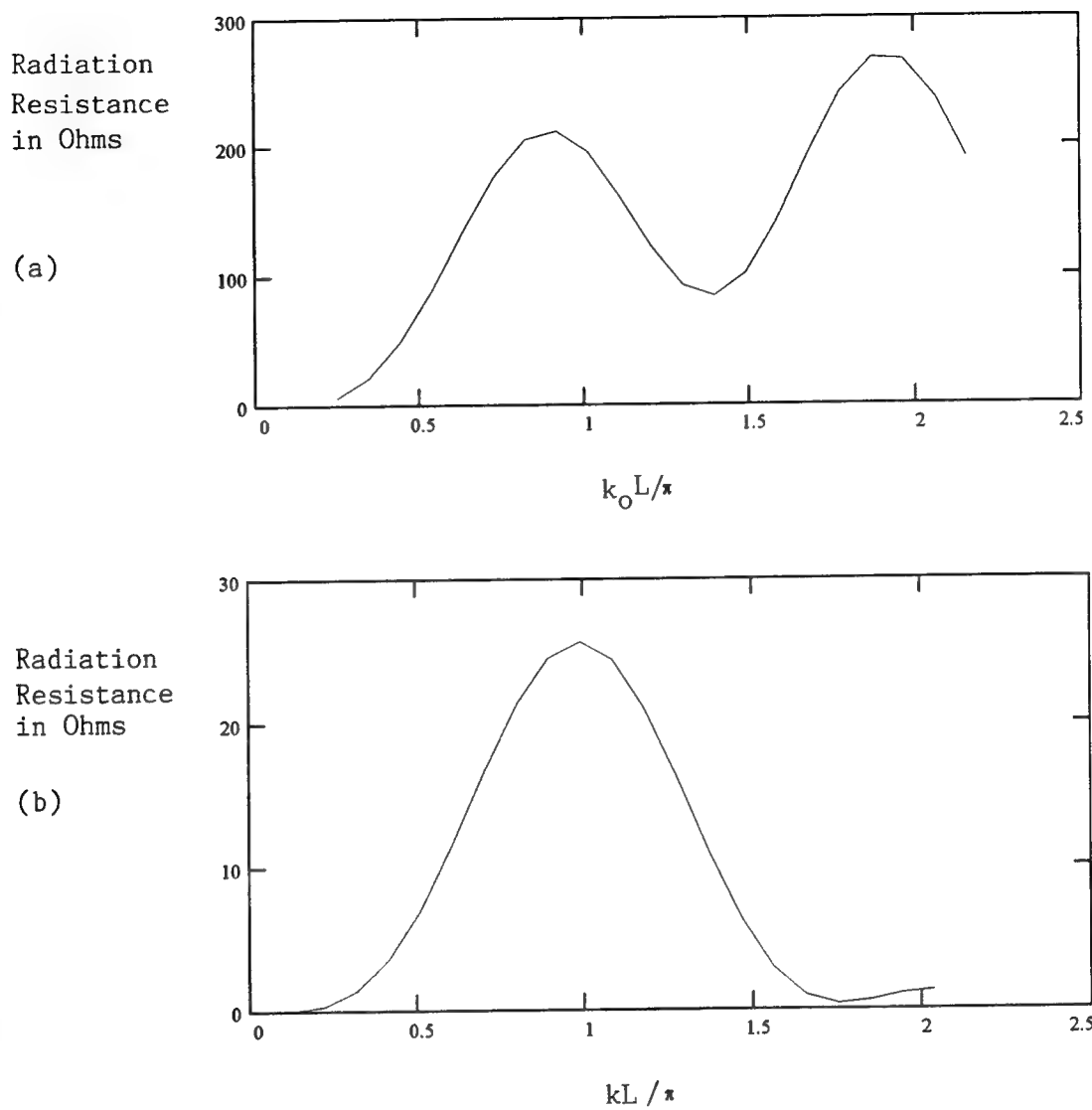


Figure 5 Radiation Resistance vs. Antenna Length
(a) Free-standing (b) Silicon

Radiation
Resistance
in Ohms

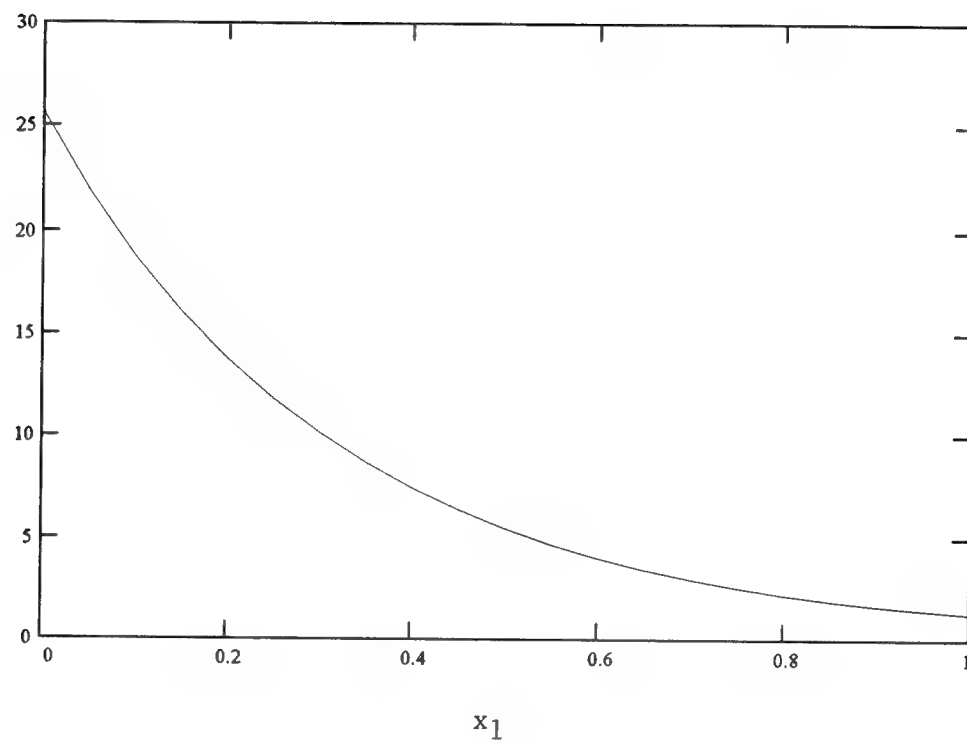


Figure 6 Radiation Resistance of a 1-wavelength Antenna
on Silicon vs. Normalized Resistance/length x_1

shortening the antenna and reducing its efficiency. The obvious solution seems to be illuminating the end of the antenna more than near the feed terminal, i.e., higher conductivity as one moves away from the terminal, more uniform current distribution can be achieved. Alternatively, for the same R_{rad} desired, less source power is needed. This is not borne out by actual calculations. Non-uniform illumination leads to a non-uniform propagation constant, the wave equation for which has no known general analytical solution. Using adiabatic approximation, valid when the rate of change of the propagation constant is slow, calculations have been made for $x_1(kz) = -0.14(kz) + 0.44$, whose average $kL = \pi$ is 0.22, same as the example above, and therefore requiring the same total optical power. The current distribution, radiation pattern, and radiation resistance are all almost indistinguishable from the uniform illumination case of $x_1 = 0.22$. In retrospect, the case of non-uniform illumination offers little advantage in comparison to the case of uniform illumination with the same total optical power: since the ends of the antenna have to be illuminated more to keep the conductance high, the parts near the terminal must be illuminated less, thus attenuating the current at the very beginning. The only situation which calls for non-uniform illumination is when a long ($>$ wavelength) antenna is desired. The source power required in such case will be high.

(d) Arrays of Linear Dipoles Arrays of antennas provide higher gains than single antennas. The maximum directional gain of a array of N antennas is N^2 times the maximum directional gain of a single antenna. The maximum directional gain of a single $1-\lambda$ antenna is only slightly higher than unity. An array of 3 provides increases the directional gain by a factor of 9 to 10, yet the optical source power needed only increases by a factor of 3 to about 1 kW, which we consider practical.

(iii) Bow-Tie Antenna

The bow-tie antenna, shown in Fig. 7a, can be understood as the sum of many triangular wire antennas each with a slightly different apex angle (Fig. 7b). The horizontal part of the current contributes little to the total radiation, thus each component dipole resonates at a slightly different frequency, leading to the broad-band characteristic of the bow-tie. In calculating the bow-tie antenna characteristics, this model of multiple line dipoles is used (Appendix I). The justification of this model lies in the good agreement between measurement [3] and calculation (Fig. 8). For an antenna on semiconductor, some problem arises due to the particular geometry of the structure. Uniform illumination of the antenna pattern leads to uniform *conductivity* along the current path. However, the width of the current path increases along the path, thus the *conductance* also increases, leading to a non-uniform propagation constant. This problem exists even for metallic antenna: one way to look at it is that as the width increases, the characteristic impedance decreases, again leading to non-uniform propagation constant. For this study, we will approximate the problem by using a constant resistance/length for each of the loops which consistute the whole bow-tie. Justification lies on the calculated linear dipoles above (cf. Section (ii-b)).

The bow tie-antenna is modeled by a series of triangular wire antennas with the apex angle separated by 2.5° . The feed terminal is at the apex, and the current is required to be zero in the middle of the base opposite the apex (Fig. 7b). Each wire is assumed to have a normalized resistance/length x_1 (Eqn 5). The total radiated field is calculated by adding the fields from each wire vectorially.

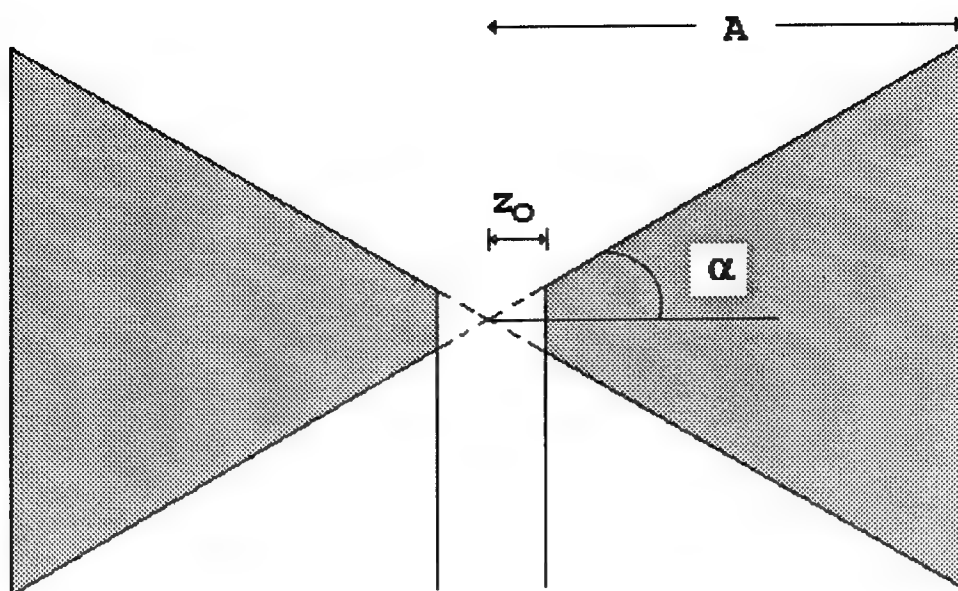


Fig 7a Bow-Tie Antenna

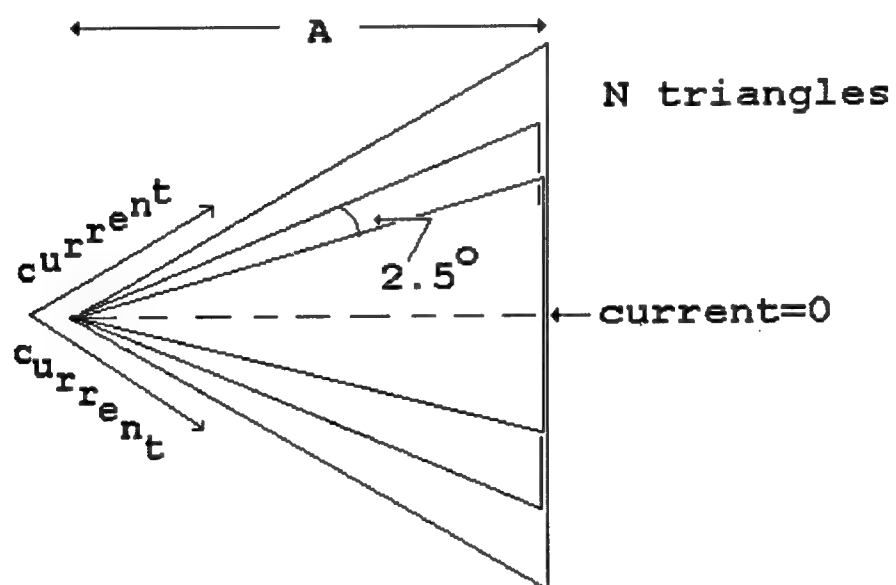
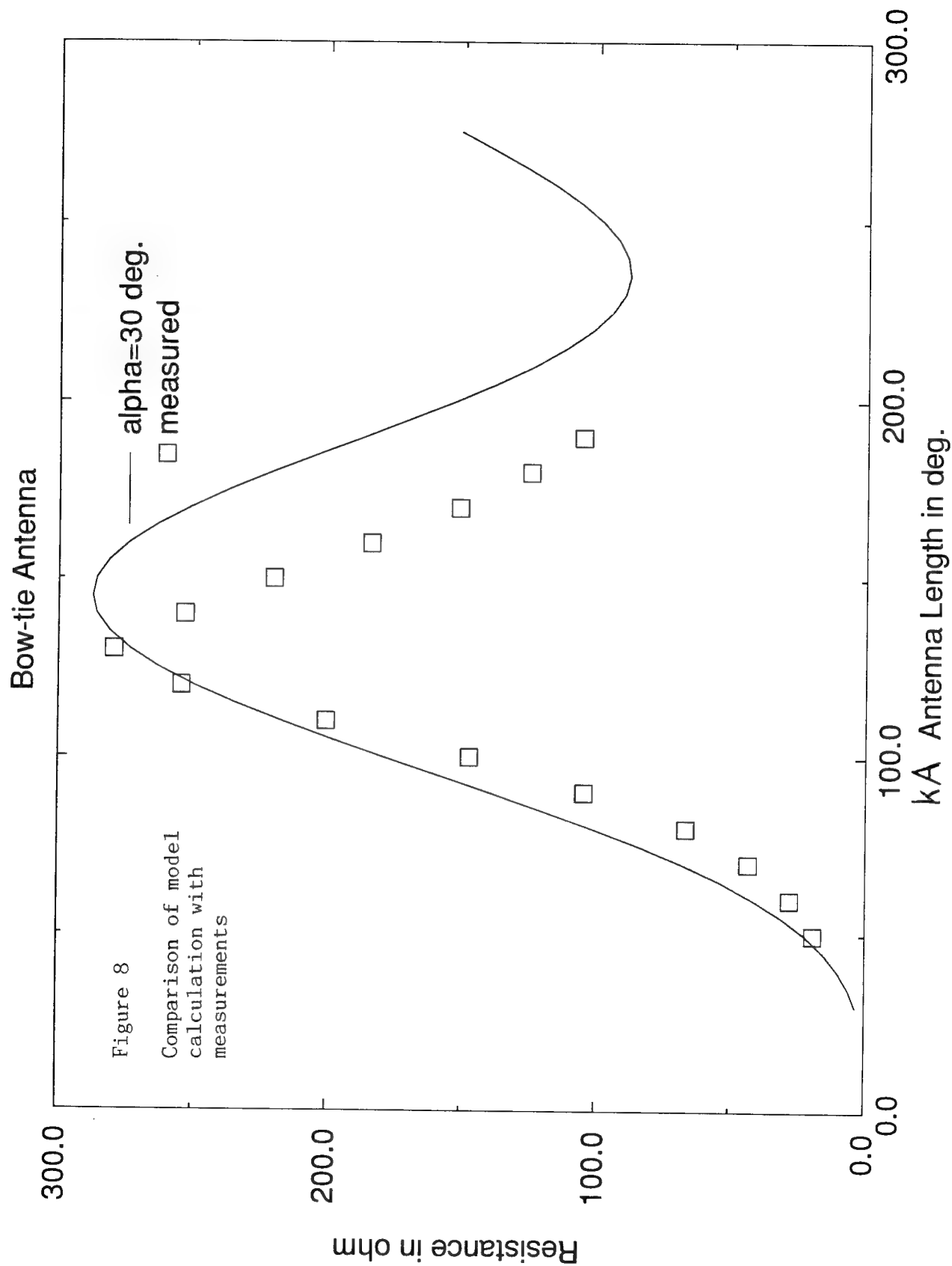


Fig 7b Model for Bow-Tie Antenna

Calculated Resistance Comparison with Measured Data



The radiation pattern and radiation resistance are calculated for a metallic free-standing bow-tie to check that they agree with measurements [3], which they do if a small amount of loss is included, which is not surprising as resistive losses are present at high frequencies even in metals. For simplicity, we will only mention, but not show any graph, that our calculations show that the gain of the bow-tie is comparable to that of the half-wave dipole, and the radiation pattern is also similar except for a slight lack of azimuthal symmetry. The major difference from the half-wave is that as the electrical length of the bow-tie is increased beyond a wavelength, the radiation resistance will not rise periodically to other peaks as in the linear case.

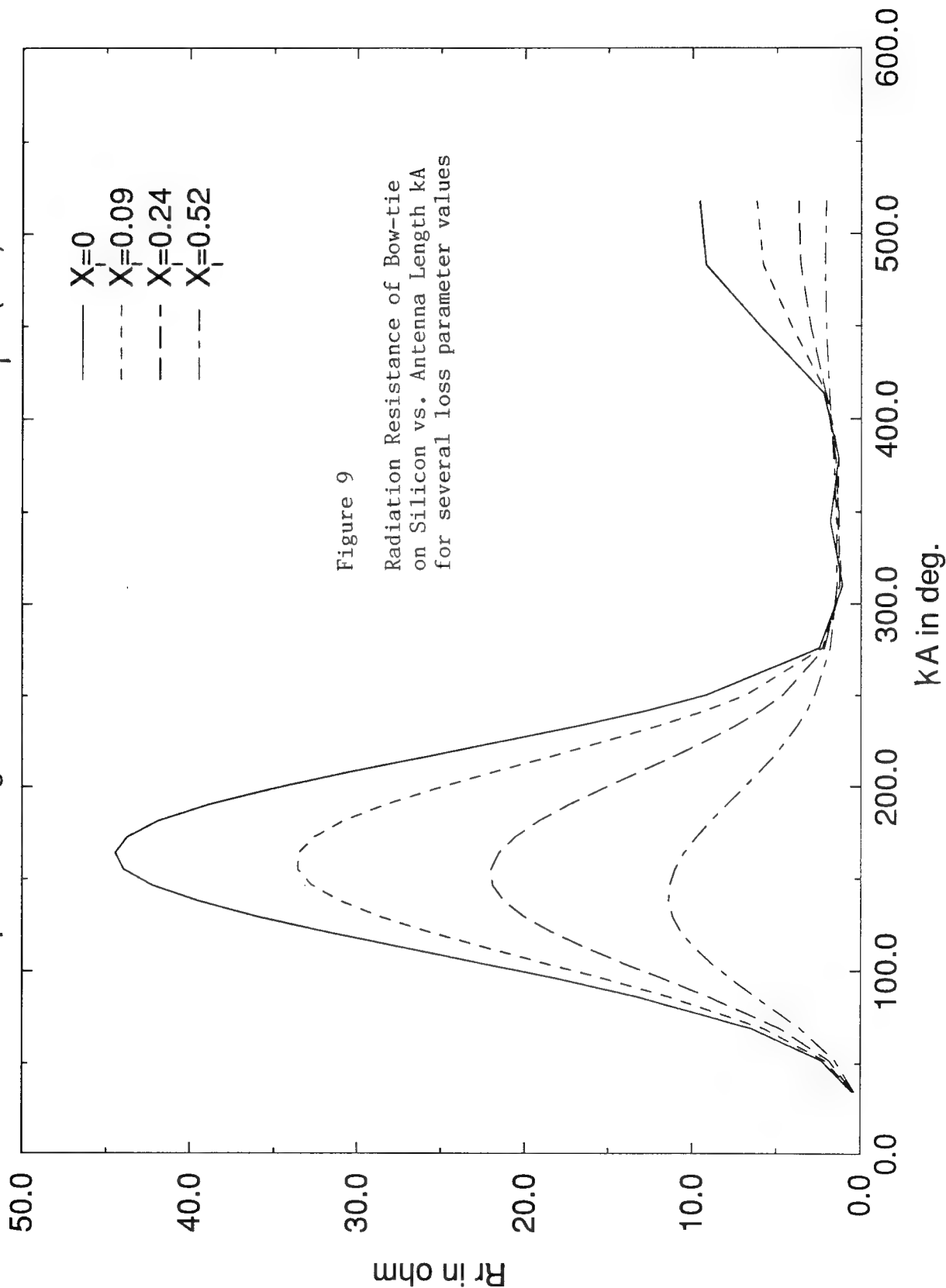
The following calculations are for a bow-tie antenna with a full angle of 60° . The radiation resistance vs electrical length kA is shown in Fig. 9 for several values of normalized resistance/length x_1 . The resistance peaks near the antenna length $2A=\lambda$ ($kA=180^\circ$), as expected. Fig. 10 shows the maximum radiation resistance vs x_1 . When $x_1=0.24$, the radiation resistance has fallen by -3db from its lossless case. To calculate the source power needed to induce this level of resistance, one equates the total resistance presented by the parallel wire antennas to the current to the total resistance presented to the sheet current in the bow-tie, and the source intensity I can be shown to be (Fig 7b):

$$I = (E_g/e) (N/2\alpha) \ln(A/z_0) / [\mu\tau(kA) Z_0]$$

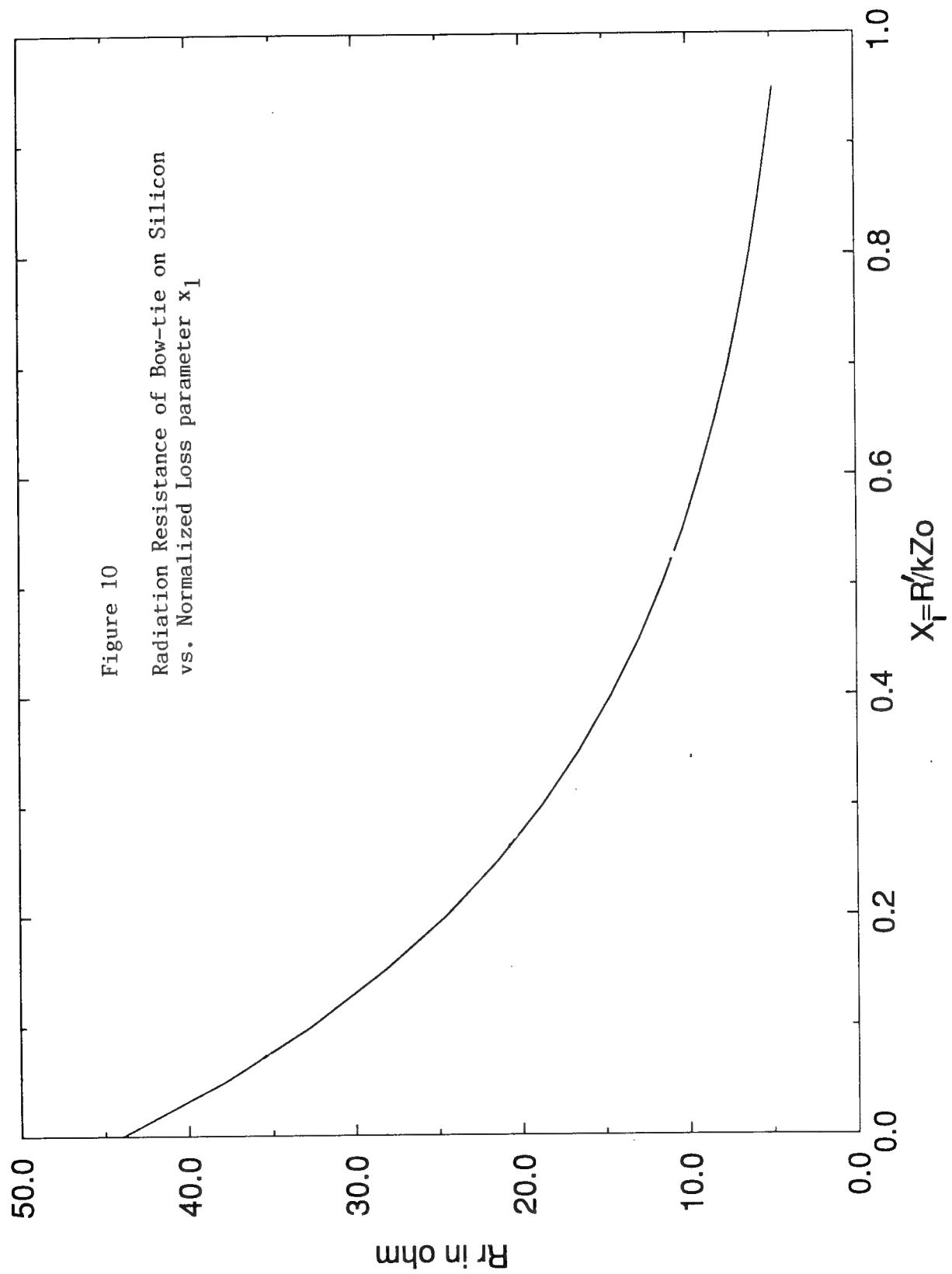
The power is the area of the bow-tie times I . For silicon and $kA=\pi$, $x=0.24$, the power needed to illuminate a circle enclosing the bow-tie is about 1 kW, again in agreement with the estimate above.

Bow-Tie Antenna Radiation Resistance R_r vs Length A

$\alpha=30$ deg. $n=3.45$ for different losses $X_l=R_l/(KZ_o)$



Rr- X



Semi-reconfigurable Antennas

Higher performance and lower source power can be achieved by trading off some degree of reconfigurability and stealth. Metallic patterns can be laid permanently on the semiconductor, and light or electrons will only be used to connect the different parts of the metallic patterns to form a complete antenna. For this application, directional sources like the laser and electron beams are suitable, and the saving in source power can be considerable, since the power required scales as the square of the distance between 2 conducting patterns (Eqn. 2). However, the cross-section of reflecting an incident radar wave increases as the area of the metallic patterns, even if the patterns are not connected.

Heating due to Optical or Electron Excitation

The heating due to optical or electron excitation can be estimated by considering the temperature rise after an excitation pulse. For the applications considered, an optical or electron pulse excites the semiconductor to write an antenna. Usually the pulse is much shorter than the thermal time constants, therefore the excitation can be regarded as an impulse whose energy deposited in the semiconductor causes a rise in temperature which subsequently decays to the ambient. The maximum rise in temperature ΔT is immediately after the excitation pulse. From the heat diffusion equation [4],

$$\Delta T = Q/\rho C$$

where Q is the energy density deposited, ρ the density of the semiconductor, and C the specific heat. In the worst case of writing line antenna, assume a width of 5 mm, optical penetration depth 0.5 μm , incident power/length of 30 W/cm, turned on for 20 μs , $\rho=2.3 \text{ gm/cm}^3$, $C=0.7 \text{ J/gm-}^\circ\text{C}$ (for silicon), then $Q=24 \text{ J/cm}^3$, and $\Delta T=15^\circ\text{C}$ which subsequently subsides. For electron excitation, the rise in temperature is 3 times as high, still insufficient to be of concern.

If the excitation pulse repetition rates increases, eventually heat cannot be conducted fast enough. To estimate the maximum rep. rate, consider the time heat takes to diffuse from one face of the silicon where it is excited to the opposite face at ambience. For a typical thickness s of 1/4 mm, the diffusion time is s^2/D , where $D=\text{diffusivity}=0.9 \text{ cm}^2/\text{s}$, or 0.7 ms, allowing a rep. rate of 1.4 kHz.

Source Requirements and Available Sources

The only practical lasers are the diode lasers which alone among lasers have efficiency of tens percent. Even they have to be cooled with thermal electric coolers for units which put out over 100 mW or so. For pulsed applications, the energy needed is about power \times (silicon carrier lifetime) or a few mJ. Commercial, table-top diode laser bars can deliver such energy levels at kHz repetition rate.

For incoherent optical sources, the consumer photographic flash lamp puts out several joules in microseconds. Even accounting for losses in collimation and spectral mismatch with semiconductors, the flash lamp delivers more than enough energy for reconfigurable antennas below 1 GHz. Repetition rates of photographic lamp systems are low, \sim Hz. However, compact flash lamp systems can be constructed up to kHz rep rate.

The vacuum field emitter arrays (FEAs) can deliver kV and μ A per tip, with power density in excess of 10 kW/cm² [5]. In comparison with optical sources, the electron FEA's are more efficient, close to 100%, and there is little back-scattering for the low energy ($<$ kV) electrons. However, once the electron enters the semiconductor, only about 30% of its energy is used for generating charge carriers. Thus the overall efficiency of the two sources are comparable, with the electrons generating 3 times more heat in the antenna. Although reliability and costs of FEAs may be of concern, the technology is under rapid development and driven by other commercial applications, which eventually will make practical electron sources available for this application.

Thus the source requirements can be met with currently available technology, with the cheapest source, the flashlamp, most appealing.

Conclusions and Recommendations

Although detailed calculations were performed on only 2 antenna structures, some general conclusions can be drawn as more general antenna structures can be viewed as superpositions of the linear antennas. First, because of the unavoidable current decay, reconfigurable antennas of dimensions much longer than a wavelength is not practical unless for extremely high frequencies. For high-gain antennas, arrays of smaller antennas, each not much larger than a wavelength, have to be used instead. For a single antenna of a wavelength long, the lowest practical frequency is about 1 GHz, which requires several watts of optical power or 1 kilowatt of electron power. The required power scales as wavelength squared.

Due to the mismatch of dielectric constants in semiconductors and air, an antenna on semiconductor, metallic or reconfigurable, is less efficient than a free-standing antenna of the same electrical structure, by a factor of roughly the ratio of permittivities, or about 10 for most semiconductors.

For wire-type antennas, well-defined conducting patterns demand directional sources like lasers and electron beams. For large aperture type antennas, large conducting patterns can use incoherent sources like the flash lamp. Laser systems of output power over 1 kW or so are expensive and bulky. Flash lamps of output energy of several joules are compact and inexpensive, as used in consumer photography. Electrons from vacuum microtips are still in the development stage, and electrons do have about only 30% efficiency in generating charge carriers in semiconductors.

For these reasons, it appears that high-performance reconfigurable antennas are expensive, if indeed practical

at all, to design and construct. The use of reconfigurable antennas should then be confined to more elementary structures, unless reconfigurability and stealth must be achieved at all cost.

However, a trade-off can be made between power and the degrees of reconfigurability and stealth on the one hand, and performance on the other. If light or electrons are used only to connect some permanent, metallic patterns to form antennas, then high-performance can be achieved at lower power at a sacrifice or complete stealth and reconfigurability.

Appendix I Mathematical Formulas and Equations

The following notations are used:

n = index of refraction of semiconductor
 λ_o = wavelength in vacuum
 k_o = wave vector in vacuum
 $k = nk_o$ = wave vector in semiconductor in lossless case
 Z_o = characteristic line impedance in lossless case
 R' = resistance/length of line
 $x_1 = R'/(kZ_o)$ = normalized resistance
 $\eta = (\mu_o/\epsilon_o)^{1/2}$ = characteristic impedance of vacuum
 $= 376 \Omega$

The following formulas and equations can be found in [2], adapted for this particular study. The propagation constant γ is defined in Eqn (4):

$$\begin{aligned}\gamma &= (j\omega C'R' - \omega^2 L'C')^{1/2} \\ &= jk(1 + x_1)^{1/2} \exp(-0.5j \tan^{-1} x_1)\end{aligned}\tag{A1}$$

Now consider a current $I(z')$ flowing in a straight line along z' which lies on the x - z plane with an angle b from the z -axis (Fig. A-1). The radiation fields can be derived from the vector quantity \mathbf{N} [2]:

$$\mathbf{N} = [\mathbf{z} \cos(b) + \mathbf{x} \sin(b)] \int I(z') \exp(jk_o z' \cos(p)) dz'\tag{A2}$$

where

$$\cos(p) = \mathbf{z}' \cdot \mathbf{r}$$

For linear dipoles of length L on the z -axis, $b=0$, $p=\theta$, boundary conditions $I(z'=\pm L)=0$. Then for input current of amplitude I_0 , the current distribution is:

$$I(z') = \begin{cases} I_0[e^{-\gamma z'} - e^{\gamma z' - 2\gamma L}] & z' > 0 \\ I_0[e^{\gamma z'} - e^{-\gamma z' - 2\gamma L}] & z' < 0 \end{cases} \quad (A3)$$

With the normalized integration variable s :

$$s = kz' \quad (A4)$$

and normalized propagation constant $g(s)$:

$$g(s) = \gamma z' \quad (A5)$$

N can be written as

$$\begin{aligned} N &= (zI_0/k) \left[\int_0^{kL} [e^{-\gamma z'} - e^{\gamma z' - 2\gamma L}] e^{j s \cos(\theta)/n} ds + \right. \\ &\quad \left. \int_{-kL}^0 [e^{-\gamma z'} - e^{\gamma z' - 2\gamma L}] e^{j s \cos(\theta)/n} ds \right] \\ &= (zI_0/k) F(kL, n, \theta) \end{aligned} \quad (A6)$$

which defines the expression F . The total power radiated into all solid angles is

$$\begin{aligned} W &= \eta I_0^2 / (2(4\pi n)^2) \int_{4\pi} d\Omega \sin^2\theta [F(kL, n, \theta)]^2 \\ &= I_0^2 / (2R_{\text{rad}}) \end{aligned} \quad (A7)$$

which defines the radiative resistance R_{rad} .

The bow-tie antenna is modeled by a number of loop antennas with b 's separated by 2.5° (Fig A2). The boundary conditions are that the currents vanish in the middle of the horizontal (parallel to x-axis) segments. For each straight segment of each loop, the angle b changes from b to 90° (horizontal part) to $-b$. The function F is calculated by summing all the F 's for each loop. The integral in Eq (A7) now depends on ϕ as well.

Appendix II Program Listing of Bow-Tie Calculations

```

/* bow_tie antenna plate simulation */
/* radiation resistance parameters : x, y, alfa */
#include <stdio.h>
#include <math.h>
#define Nz 25
#define N 200
#define n 3.45
#define pi 3.141592654
#define dALFA 2.5
#define ALFA 30.
/* -o c05.out */
main()
{
    FILE *fopen(), *pout;
    double theta, dtheta, Kr, Rr, fi, dfi;
    double Nx(), Nxi(), Nzz(), Nzi(), N3r(), N3i();
    double sum1, sum2, s1, s2;
    double alfa[37], y[37], Ntheta[37], Nfi[37], Nthetai[37], Nfii[37];
    double c1, c2, c3, c4;
    double A, A1, wavelength, x1;
    double Am, Rm, M;
    int j1, j2, j, q, N0, i;
    M= ALFA/dALFA+0.5;
    M=floor(M);
    Am=0.; Rm=0.;
    wavelength=0.5; /*f=600MHz*/
    for (i=1; i<(M+1); i++)
    {
        alfa[i]=dALFA*i*pi/360;
    }
    pout=fopen("nx30R300A1.dat", "w");
    x1=0.24;
    A=15.;
    for (q=1; q<=1; q++)
    {
        A1=A*wavelength/360;
        for (i=1; i<(M+1); i++)
        {
            y[i]=A1/(wavelength*cos(alfa[i])/4);
        }
        N0=N/2;
        dtheta=pi/N0;
        dfi=2*pi/N;
        sum1=0.0; theta=0.0;
        for (j1=0; j1<=(N0/2); j1++)
        {
            if((j1%2) ==0) s1=2.0;
            else
            s1=4.;
            if(j1==0 || j1==N0/2) s1=1.;
            sum2=0.0; fi=0.0;
            for (j2=0; j2<=(N/4); j2++)
            {
                if((j2%2) ==0) s2=2.0;
                else
                s2=4.;
                if(j2==0 || j2==N/4) s2=1.;
                for (i=1; i<(M+1); i++)
                {
                    Ntheta[i]=(Nx(x1, y[i], alfa[i], theta, fi)+N3r(x1, y[i], alfa[i], theta, fi));
                    Ntheta[i]=Ntheta[i]*cos(fi)*cos(theta);
                    Ntheta[i]=Ntheta[i]-Nzz(x1, y[i], alfa[i], theta, fi)*sin(theta);

                    Nfi[i]=(Nx(x1, y[i], alfa[i], theta, fi)+N3r(x1, y[i], alfa[i], theta, fi))*sin(fi);
                }
            }
        }
    }
}

```



```

Nthetai[i]=(Nxi(x1,y[i],alfa[i],theta,fi)+N3i(x1,y[i],alfa[i],theta,fi));
Nthetai[i]=Nthetai[i]*cos(fi)*cos(theta);
Nthetai[i]=Nthetai[i]-Nzi(x1,y[i],alfa[i],theta,fi)*sin(theta);

Nfii[i]=(-Nxi(x1,y[i],alfa[i],theta,fi)+N3i(x1,y[i],alfa[i],theta,fi))*sin(fi);
}
c1=0.; c2=0.; c3=0.; c4=0.;
for (i=1;i<(M+1);i++)
{
c1=c1+Nthetai[i];
c2=c2+Nthetai[i];
c3=c3+Nfi[i];
c4=c4+Nfii[i];
}

Kr=(c1*c1+c2*c2+c3*c3+c4*c4);
sum2=sum2+s2*Kr*sin(theta);
fi=fi+dfi;
}
sum2=sum2*dfi/3;
sum1=sum1+s1*sum2;
theta=theta+dtheta;
}
Rr=30*pi*sum1*dtheta/3;
Rr=Rr/((M)*(M));
Rr=Rr/2;
Rr=Rr*8;
fprintf(pout,"%e %e\n",A, Rr);
printf("%e %e\n",A, Rr);
A=A+5.;
}

double Nx(x1,y,alfa,theta,fi)
double x1,y,alfa,theta,fi;
{
double x,z,dz,v,u,sum,s,J,J1,p1,n1,f;
int i;
z=0.1;
sum=0;
dz=1./Nz;
for (i=0;i<=Nz;i++)
{
x=x1;
f=atan(x)/2;
v=n*0.5*pi*pow((1+x*x),0.25)*sin(f);/* v=0.5*pi*a */
u=n*0.5*pi*pow((1+x*x),0.25)*cos(f);/* u=0.5*pi*b */
n1=0.5*pi*y*sin(alfa)*sin(theta)*cos(fi);
p1=0.5*pi*y*cos(alfa)*cos(theta);
if((i%2) ==0)s=2.0;
else
s=4.;
if(i==0 || i==Nz)s=1.;
J=cos(u*y*(1+sin(alfa)))*cos(u*y*(1+sin(alfa)-(z)))*sinh(v*y*(1+sin(alfa)-(z)));
J=J+sin(u*y*(1+sin(alfa)))*sin(u*y*(1+sin(alfa)-(z)))*cosh(v*y*(1+sin(alfa)-(z)));
sum=sum+s*y*exp(-v*y*(1+sin(alfa)))*J*sin(n1*(z))*sin(p1*(z));
z=z+dz;
}
J1=-sum*dz/(3.);
return(J1);
}

double Nxi(x1,y,alfa,theta,fi)
double x1,y,alfa,theta,fi;
{
double x,z,dz,v,u,sum,s,L,L1,p1,n1,f;

```

```

int i;
z=0.1;
sum=0;
dz=1./Nz;
for (i=0;i<=Nz;i++)
{
x=x1;
f=atan(x)/2;
v=n*0.5*pi*pow((1+x*x),0.25)*sin(f);/* v=0.5*pi*a */
u=n*0.5*pi*pow((1+x*x),0.25)*cos(f);/* u=0.5*pi*b */
n1=0.5*pi*y*sin(alfa)*sin(theta)*cos(fi);
p1=0.5*pi*y*cos(alfa)*cos(theta);
if((i%2) ==0)s=2.0;
else
s=4.;
if(i==0 || i==Nz)s=1.;
L=cos(u*y*(1+sin(alfa)))*sin(u*y*(1+sin(alfa)-(z)))*cosh(v*y*(1+sin(alfa)-(z)));
L=L-sin(u*y*(1+sin(alfa)))*cos(u*y*(1+sin(alfa)-(z)))*sinh(v*y*(1+sin(alfa)-(z)));
sum=sum+s*y*exp(-v*y*(1+sin(alfa)))*L*sin(n1*(z))*sin(p1*(z));
z=z+dz;
}
L1=-sum*dz/(3.);
return(L1);
}

```

```

double Nzz(x1,y,alfa,theta,fi)
double x1,y,alfa,theta,fi;
{
double x,z,dz,v,u,sum,s,J,J1,p1,n1,f;
int i;
z=0.1;
sum=0;
dz=1./Nz;
for (i=0;i<=Nz;i++)
{
x=x1;
f=atan(x)/2;
v=n*0.5*pi*pow((1+x*x),0.25)*sin(f);/* v=0.5*pi*a */
u=n*0.5*pi*pow((1+x*x),0.25)*cos(f);/* u=0.5*pi*b */
n1=0.5*pi*y*sin(alfa)*sin(theta)*cos(fi);
p1=0.5*pi*y*cos(alfa)*cos(theta);
if((i%2) ==0)s=2.0;
else
s=4.;
if(i==0 || i==Nz)s=1.;
J=cos(u*y*(1+sin(alfa)))*cos(u*y*(1+sin(alfa)-(z)))*sinh(v*y*(1+sin(alfa)-(z)));
J=J+sin(u*y*(1+sin(alfa)))*sin(u*y*(1+sin(alfa)-(z)))*cosh(v*y*(1+sin(alfa)-(z)));
sum=sum+s*y*exp(-v*y*(1+sin(alfa)))*J*cos(n1*(z))*cos(p1*(z));
z=z+dz;
}
J1=sum*dz/(3.);
return(J1);
}

```

```

double Nzi(x1,y,alfa,theta,fi)
double x1,y,alfa,theta,fi;
{
double x,z,dz,v,u,sum,s,L,L1,p1,n1,f;
int i;
z=0.1;
sum=0;

```

```

dz=1./Nz;
for (i=0;i<=Nz;i++)
{
x=x1;
f=atan(x)/2;
v=n*0.5*pi*pow((1+x*x),0.25)*sin(f);/* v=0.5*pi*a */
u=n*0.5*pi*pow((1+x*x),0.25)*cos(f);/* u=0.5*pi*b */
n1=0.5*pi*y*sin(alfa)*sin(theta)*cos(fi);
p1=0.5*pi*y*cos(alfa)*cos(theta);
if((i%2) ==0)s=2.0;
else
s=4.;
if(i==0 || i==Nz)s=1.;
L=cos(u*y*(1+sin(alfa)))*sin(u*y*(1+sin(alfa)-(z)))*cosh(v*y*(1+sin(alfa)-(z)));
L=L-sin(u*y*(1+sin(alfa)))*cos(u*y*(1+sin(alfa)-(z)))*sinh(v*y*(1+sin(alfa)-(z)));
sum=sum+s*y*exp(-v*y*(1+sin(alfa)))*L*cos(n1*(z))*cos(p1*(z));
z=z+dz;
}
L1=sum*dz/(3.);
return(L1);
}

double N3r(x1,y,alfa,theta,fi)
double x1,y,alfa,theta,fi;
{
double x,z,dz,v,u,sum,s,L,L1,p1,n1,f,z1;
int i;
z=0.1;
sum=0;
dz=1./Nz;
for (i=0;i<=Nz;i++)
{
x=x1;
f=atan(x)/2;
v=n*0.5*pi*pow((1+x*x),0.25)*sin(f);/* v=0.5*pi*a */
u=n*0.5*pi*pow((1+x*x),0.25)*cos(f);/* u=0.5*pi*b */
n1=0.5*pi*y*sin(alfa)*sin(theta)*cos(fi);
p1=0.5*pi*y*cos(alfa)*cos(theta);
if((i%2) ==0)s=2.0;
else
s=4.;
if(i==0 || i==Nz)s=1.;
z1=(1+sin(alfa)*(1-z));
L=cos(u*y*(1+sin(alfa)))*sin(u*y*(1+sin(alfa)-(z1)));
L=L*cosh(v*y*(1+sin(alfa)-(z1)))*sinh(v*y*(1+sin(alfa)-z1));
L=L-sin(u*y*(1+sin(alfa)))*cos(u*y*(1+sin(alfa)-z1))*sinh(v*y*(1+sin(alfa)-z1));
L1=s*y*exp(-v*y*(1+sin(alfa)))*(0.5*sin(alfa))*L;
L1=L1*sin(0.5*pi*y*sin(theta)*sin(fi)*sin(alfa)*z1);

sum=sum+L1;
}
L1=-sum*dz/(3.);
return(L1);
}

double N3i(x1,y,alfa,theta,fi)
double x1,y,alfa,theta,fi;
{
double x,z,dz,v,u,sum,s,J,J1,p1,n1,f,z1;
int i;
z=0.1;
sum=0;
dz=1./Nz;
for (i=0;i<=Nz;i++)
{
x=x1;

```

```

f=atan(x)/2;
v=n*0.5*pi*pow((1+x*x),0.25)*sin(f);/* v=0.5*pi*a */
u=n*0.5*pi*pow((1+x*x),0.25)*cos(f);/* u=0.5*pi*b */
n1=0.5*pi*y*sin(alfa)*sin(theta)*cos(fi);
p1=0.5*pi*y*cos(alfa)*cos(theta);
if((i%2) ==0)s=2.0;
else
s=4.;
if(i==0 || i==Nz)s=1.;
z1=(1+sin(alfa)*(1-z));
J=cos(u*y*(1+sin(alfa)))*cos(u*y*(1+sin(alfa)-(z1)))*sinh(v*y*(1+sin(alfa)-(z1)
));
J=J+sin(u*y*(1+sin(alfa)))*sin(u*y*(1+sin(alfa)-(z1)))*cosh(v*y*(1+sin(alfa)-(z1)
));

sum=sum+s*y*exp(-v*y*(1+sin(alfa)))*(-0.5*sin(alfa))*J*sin(0.5*pi*y*sin(theta)*sin(
fi)*sin(alfa)*z1);
z=z+dz;
}
J1=-sum*dz/(3.);
return(J1);
}

```

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2. Do any specific areas of the report stand out as exceptional?

Yes___ No___

If yes, please identify the area(s), and comment on what
aspects make them "stand out."

3. Do any specific areas of the report stand out as inferior?

Yes___ No___

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4. Please utilize the space below to comment on any other aspects of the report. Comments on both technical content and reporting format are desired.